CR 147899

SPECIAL REPORT TO THE
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
KENNEDY SPACE CENTER

ECOLOGICAL EFFECTS AND ENVIRONMENTAL FATE
OF
SOLID ROCKET EXHAUST

(GRANT NO. NGR 10-019-009)

(NASA-CR-147899) FIELD EXPOSURE OF TWO UPLAND COVER TYPES TO SOLID ROCKET MOTOR FUEL EMISSIONS (Florida Technological Univ.) 22 p

N77-80210

Unclas
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MARCH, 15, 1976
OFFICE OF RESEARCH AND GRADUATE STUDIES
FLORIDA TECHNOLOGICAL UNIVERSITY
ORLANDO, FLORIDA

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FIELD EXPOSURE OF TWO UPLAND COVER TYPES TO SOLID ROCKET MOTOR FUEL EMISSIONS

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Abstract: A series of replicated field experiments in which two important upland cover types were exposed to solid rocket motor fuel emissions did not reveal any immediate impact on the vegetation. Soil pH and Cl^- concentrations remained unchanged. Root biomass one year after exposures was not significantly different among the treatments. Likewise, twig growth of two browse species, Quercus minima and Quercus myrtifolia, was unimpaired. Flower and fruit formation by oaks, saw palmetto, and blueberries appeared normal one year after exposure. Litter fractions (twigs, leaves, and fine material) were not significantly different among treatment groups.

INTRODUCTION

The ecological effects and environmental fate of solid rocket motor (SRM) exhaust in and around the Kennedy Space Center (KSC) represents an area of concern to the National Aeronautics and Space Administration (NASA). Over the next several years (1978-1981) an operational Space Shuttle which employs SRM's is anticipated to be launched at KSC on a routine basis (reviewed by von Braun 1972). This aerospace activity may be expected to continue for perhaps several decades. Solid rocket motor emission products, therefore, will continue for many years to enter the various ecosystems making up Merritt Island and the Kennedy Space Center.

The purpose of this research was to determine if single and short-term exposure (10 min.) of selected ecosystems to SRM fuel emissions would result in demonstrable changes in certain response parameters. Field studies commenced in July 1973 when permanent study areas were selected in undisturbed plant communities representative of pine flatwoods and scrubby flatwoods ecosystems and baseline data on soil variables and plant abundance were gathered. Exposures of the intact plant communities were carried out in August 1974. Field observations continued and final data gathering was completed in July 1975.

We are grateful to Gary Byerley and Dean Goodall for assistance with the field work; Jim Poppleton aided with plant identifications. William Lee of the Kennedy Space Center extended many courtesies for which we are grateful. Robert Yoder and Jim Baker of the Fish and Wildlife Service provided acess to Merritt Island National Wildlife Refuge. We are grateful to NASA/KSC for support through Grant No. NGR-10-019-009.

MATERIALS AND METHODS

Study Areas

The Kennedy Space Center occupies most of Merritt Island on Florida's east central coast. Merritt Island National Wildlife Refuge shares a common boundary with KSC. The newly created Canaveral National Seashore is contiguous with and to the North of the refuge. The Eastern Test Range, under control of the U.S. Air Force, is found on the southern portion of Cape Canaveral.

Merritt Island is subtropical in its climate. Summer temperatures range from daily highs in the 90's to night time lows of 70-80F. Winter temperatures average 65F during the day and freezing conditions are seldom realized. Rainfall averages 50-55 inches per year, with an uneven distribution throughout the year (Bufson and Prine 1968). Rain is concentrated in the period of June-September while the winter months may be quite dry.

Pine Flatwoods - This ecosystem is a counterpart of a community type found widely over peninsular Florida (Laessle 1942). The typical overstory of longleaf pine (Pinus palustris) is not present in the stands studied on northern Merritt Island, but a typically developed understory of broadleaf evergreen shrubs is present. Study of 40 systematically located 1-m^2 plots revealed 9 dominant woody plants on the study plots. Dwarf live oak (Quercus minima) occurred at a density of 20.2/m^2. Saw palmetto (Serenoa repens) was very conspicuous but less dense (0.8/m^2). Shiny lyonia (Lyonia lucida) and shiny blueberry (Vaccinium myrsinites) were common elements.

The pine flatwoods study plots are found on Immokalle sand soil type (Huckle, et al. 1974). The soil is dark gray and highly acid (pH 4.5).

Drainage is poor and standing water may be present for short periods during the summer months.

Scrubby Flatwoods - This ecosystem is very similar to the sandpine scrub communities that occupy well drained sands in many parts of Florida (Laessle 1958). The coastal examples of these communities on Merritt Island lack the sandpine (Pinus clausa) overstory. Our sampling (40 1-m^2 plots) revealed 10 common scrub species. Three oaks were dominant elements based on density. Myrtle oak (Quercus myrtifolia) was most prevalent (10.1/m^2) and Chapman (Quercus chapmanii) and dwarf life oak (Quercus minima) were less important, 3.9 and 4.3/m^2. Three Lyonia species were present, viz., L. fruiticosa, L. ferruginea, and L. lucida. Saw palmetto occurred at the same density (0.8/m^2) as in the pine flatwoods study area.

The scrubby flatwoods study plots are found on the Pomello sand soil type (Huckle et al. 1974). The soil is light gray and has a pH of 5.0. Permeability is rapid and the communities are not subject to flooding during the rainy season.

Research Design and Exposures

Experimental design for the pine flatwoods and scrubby flatwoods communities was identical. Eight plots were exposed to SRM emission products in each community type. Four treatments, based on theoretical concentration in SRM fuel exhaust, viz., control, 5, 50 and 100 ppm HCl, were replicated in each community. Plots were identified in the field and assigned to treatment levels according to a randomized complete block design (Steel and Torrie 1960).

Each plot was 3.16 m on a side (10-m^2). A field enclosure rested over the vegetation and confined the exhaust gases for a period of 10 minutes. The enclosure was constructed of four side panels and two hinged roof panels. Each panel was 3.16- x 1.67-m. Construction was of 5.08- x 5.08-cm cedar framing with 6-mil polyethylene transparent plastic walls. Walls and roof were designed to erect in the field with clamps and guylines to provide rigidity. Total volume enclosed was 16.7-m^3.

Exhaust components (Table 1) from SRM fuel were generated by open burning of pre-weighted quantities of SRM fuel. Fuel was placed on a sand substratum within an open-topped metal cylinder which served to shield the plants from thermal damage. Ignition was accomplished electronically after the fuel was attached with nichrome wire (0.010 in diam.) to lead wires from a battery box located outside the enclosure.

An impinger gas sampling system was used to determine dosage. All components of the exhaust could not be independently ascertained; therefore, HCl was monitored with a system Madsen (1974) developed for laboratory and field use. Air from the enclosure atmosphere was continuously drawn by a vacuum pump thru a gas dispersion tube and trapped in deionized water. The chloride content of the deionized water was then related to the HCl content of the enclosure atmosphere. Routine calculation of HCl concentration was carried out by direct potentiometric determination of chloride. A calibration curve was prepared based on standard chloride solutions and results expressed in ppm HCl.

Response Parameters

Studies on soil variables were limited to monitoring pH and Cl^- concentration. Multiple soil samples were collected from the study sites

prior to and following exposure to SRM fuel exhaust. Soil pH was determined by the 1:1 soil:water ratio method. The pH of the resulting suspension was measured with a previously calibrated Beckman Expandomatic pH meter operated in the standard range. Silver-silver chloride indicator and reference electrodes were employed to determine chloride content of the soil suspensions.

Structural conditions of leaves of plants growing within the study plots were documented with line drawings, notes, and color photographs prior to exposure. Four to six woody plants were identified and three branches (top, middle, and bottom of the canopy) tagged for sequential observation of three terminal leaves per branch.

Possible delayed effects of SRM exhaust on the vegetation were studied in July 1975. Treatment effects on root biomass were evaluated by taking ten 1- x 25-cm soil cores from each plot using objective procedures. Cores from a given plot were pooled and the root material separated from the soil by use of a No. 20 seive. Root biomass was oven dried 40 hrs. at 58C and weighed to the nearest 0.1 g.

Twig growth was studied by clipping current growth and determining dry weight. Within the pine flatwoods area only Quercus minima was suitable for this measurement. Ten twigs were collected from a single individual (judged to be typical) in each plot. The same procedures were used in sampling from the scrubby flatwoods plots. Owing to their abundance, two individuals of Quercus myrtifolia per plot were sampled. All twigs were oven dried 40 hrs. at 58C and their mass individually determined on a Mettler H542 microbalance.

Within each plot on the two study areas, two 0.1-m^2 quadrants were objectively located and all plant litter (leaves, twigs and fine

particulate matter) was collected. Material passing through a screen with ~~a screen with~~ a 2- x 2-mm mesh was discarded. Woody material was handpicked and the remaining fraction sorted into fine material with a screen of 6- x 6-mm mesh. Material not passing through the screen was defined as leaves. All fractions were oven dried for 40 hrs. at 58C and the mass determined.

RESULTS

Theoretical and atmospheric concentrations of HCl in the field enclosure are given in Table 2 according to cover type. All fuel was ignited in each exposure; therefore, the expected concentrations were probably reached for some brief period. Differences between theoretical and observed values may be explained by adsorption of the emission products (including HCl) on the foliage and enclosure walls. The data suggested some vertical stratification in the enclosure with concentration increasing with height.

Soil

Analysis of variance of interaction between treatments and soil pH in the pine flatwoods 10 days after exposure to SRM fuel exhaust indicated no differences among the plots ($F = 1.708$, df 1 and 7, NS). A similar analysis of the scrubby flatwoods revealed no treatment effect ($F = 0.435$, df 1 and 7, NS).

Mean Cl^- concentrations in soil samples from the replicate plots are presented in Table 3. Plots were exposed to SRM fuel exhaust 10 days prior to the September observations. Inspection of these data suggests no detectable change in soil Cl^- was apparent between April and September.

Impact On Leaf Structure

Visual inspection of leaves on labeled plants immediately after exposure, 2 weeks, and 4 weeks post-exposure revealed no discernable damage. Previous work with laboratory plants (Stout unpublished work) had confirmed typical kinds of damage to be expected, e.g., acid burns. No further inspection of leaves on the plots was made after 4 weeks.

Root Biomass

The relationship between root biomass and exposure concentration on the pine flatwoods plots one year after exposure was described by the equation $y = 19.83 + 0.02(x)$, where y is root biomass and x is the theoretical concentration of HCl in the SRM fuel exhaust (Fig. 1). The coefficient of determination (r^2) was 0.1024 and indicated little of the variation in root biomass was explained by the treatments. Similarily, the equation $y = 14.30 - 0.03(x)$ fit the root biomass data from the scrubby flatwoods area. Little variation in root biomass was accounted for by the treatments ($r^2 = -0.1024$).

Twig Growth

Mean dry weight of dwarf live oak twigs from the pine flatwoods plots are in Table 4. No treatment effects were demonstrated ($F = 2.628$, 3 and 3 df, NS).

Dry weights of myrtle oak twigs from scrubby flatwoods plots are presented in Table 5. Analysis of these data indicated heterogenity among the means ($F = 7.097$, 3 and 12 df, $p < .05$). The control and 100 ppm treatment groups were significantly different ($t = -4.059$, 6 df, $p < .05$), the exposed plants were larger than the controls. No other group was significantly different from the controls ($p > .05$).

Flowering and Fruiting

Observations in July 1975 on the pine flatwoods and scrubby flatwoods indicated that fruiting and flowering of shrubs such as the oaks, saw palmetto, and blueberries, were normal. These qualitative data are summarized in Stout (1975:64-65).

Litter Standing Crop

Standing crop of litter components on the pine and scrubby flatwoods plots are given in Tables 6 and 7. Analysis of variance of treatment and litter components on the pine flatwoods was not significant ($P > .05$). A similar analysis of treatments effects on the scrubby flatwoods indicated no significant differences among plots ($p > .05$).

DISCUSSION

The basic question being ask by this work was will wildlife habitat be significantly altered by single, and short-term exposure to SRM emission products. Exposure of natural vegetation to the total complex of emission products appeared to be a realistic way to help answer the question. Furthermore, we assumed that the potential impact of greatest concern to long-term stability of the habitats was the disruption of plant growth and reproduction, i.e., primary production (Woodwell 1970).

Indirect but subtle changes in soil chemistry could influence plant growth. Exposure to SRM fuel emission products did not result in changes in soil pH and Cl^- concentration on the study plots. A reduced soil pH would have made soluble aluminum more available and lead to toxic conditions for wildlife food plants (Clarkson 1969). Input of Al_2O_3

was not likely to cause any alteration in growing conditions because of its stability and abundance in the soil. Buckman and Brady (1969:24) state that from 4.5 to 13.14 percent of soil is Al_2O_3.

No structural damage in the form of acid burns, chlorosis, margin curl or pitting was observed on leaves of plants exposed in the field. Heck et al. (1970) reviewed the scanty literature on hydrogen chloride as a phytotoxin. They list, among other plants, maple (Acer sp.), cherry (Prunus sp.) larch (Larix sp.), and viburnum (Viburnum sp.) as sensitive to HCl; whereas, oaks, spruce (Picea sp.), and some maples are resistant. Lind and London (1971) found marigold (Tagetes sp.) exhibited no visible effect when exposed to 95 ppm HCl. A spectrum of sensitivities might be expected in a natural community, comprised of numerous species. The lack of evidence of sensitivity to SRM fuel emissions in our studies is probably best explained by natural resistance. All the plants are adapted to grow in xeric environments with nutrient deficient soils. Evergreeness and thick, leathery leaves are morphological features which further aid in provision of resistance to SRM fuel emissions (Seddon 1974:71).

The importance of oaks and other scrub species as cover and food for wildlife in general and deer specifically (Harlow and Jones 1965:100) prompted a re-examination of the study areas a year after the exposures. Laboratory studies of HCl gas (Godish 1970) have shown it to effect photosynthesis and respiration of tomato plants. Thus lack of overt damage to our study plants did not preclude delayed responses in terms of diminished growth or flower and fruit formation. However, no differences

in root biomass, twig growth of oaks, flower and fruit formation, or litter production were found.

A major deficiency of our study is a lack of replication in other seasons. However, based on our experience with two upland cover types, single and short-term exposure to SRM fuel emission products did not have an influence on the variables under study after one year.

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Table 1. Major theoretical combustion products of solid rocket motor fuel and the weight of these products during the launch of a Titan III-C booster.

Product	Form	Mole Fraction Vickers 1974	Kg per Launch NASA Anon Undated	Kg per Launch Cesta and McLouth 1969
H_2	Gas	0.32008	7,582	7,774
CO	Gas	0.25761	84,898	98,899
HCl	Gas	0.14744	63,106	75,871
H_2O	Gas	0.09663	20,657	38,772
N_2	Gas	0.07801	2,724	3,795
Al_2O_3	Solid	0.07708	95,616	116,878
CO_2	Gas	0.01407	8,535	11,332
H	Gas	0.00506	-	-
Cl^-	Gas	0.00170	-	-
$FeCl_2$	Solid	-	1,226	-

Table 2. Theoretical and atmospheric concentrations of HCl (ppm) as measured in 16.7-m^3 field enclosure after open burning of SRM fuel. Three impingers were located at 0.4-m and two at 1.0-m.

Theoretical Concentration of HCl (ppm)	Mean ± SE concentration of HCl (ppm)			
	Pine Flatwoods		Scrubby Flatwoods	
	0.4-m (n = 6)	1.0-m (n = 4)	0.4-m (n = 6)	1.0-m (n = 4)
5 ppm	1.98±0.50	1.89±0.44	0.46±0.13	0.27±0.04
50 ppm	6.45±1.02	7.37±2.29	3.05±0.55	10.12±3.24
100 ppm	13.16±1.71	16.85±1.30	6.55±1.17	22.97±7.00

Table 3. Soil Cl^- concentrations on the study plots prior to and following exposure to various concentrations of SRM fuel emissions.

Community	Treatment (ppm HCl)	Mean soil Cl^- concentration (ppm)	
		April 1974	September 1974[a]
Pine Flatwoods			
	Control n = 2	66	51
	5 ppm n = 2	24	19.5
	50 ppm n = 2	28	26
	100 ppm n = 2	29	36
Scrubby Flatwoods			
	Control n = 2	20.5	26
	5 ppm n = 2	18.5	21
	50 ppm n = 2	24.5	20
	100 ppm n = 2	17	17

[a] Exposures were in August 10 days prior to determination.

Table 4. Dry weight of early summer (July 1975) twig growth of dwarf live oak (Quercus minima) from a pine flatwoods community. Plots were exposed to SRM fuel emissions during August 1974.

Treatment (ppm HCl)		Mean ±SE dry weight of twigs (g)
Control	n = 2	0.056±.012
5 ppm	n = 2	0.100±.008
50 ppm	n = 2	0.132±.035
100 ppm	n = 1[a]	0.042±.010

[a] One plot was destroyed prior to measurement.

Table 5. Dry weight of early summer (July 1975) twig growth of myrtle oak (Quercus myrtifolia) from a scrubby flatwoods community. Plots were exposed to SRM fuel emissions during August 1974.

Treatment (ppm HCl)		Mean ±SE dry weight of twigs (g)
Control	n = 4	.122±.017
5 ppm	n = 4	.126±.042
50 ppm	n = 4	.158±.061
100 ppm	n = 4	.271±.071[a]

[a] A t-test comparison of the control and the 100 ppm treatment yields a value of -4.059 ($t_{.05}$ and 6 df = 2.447).

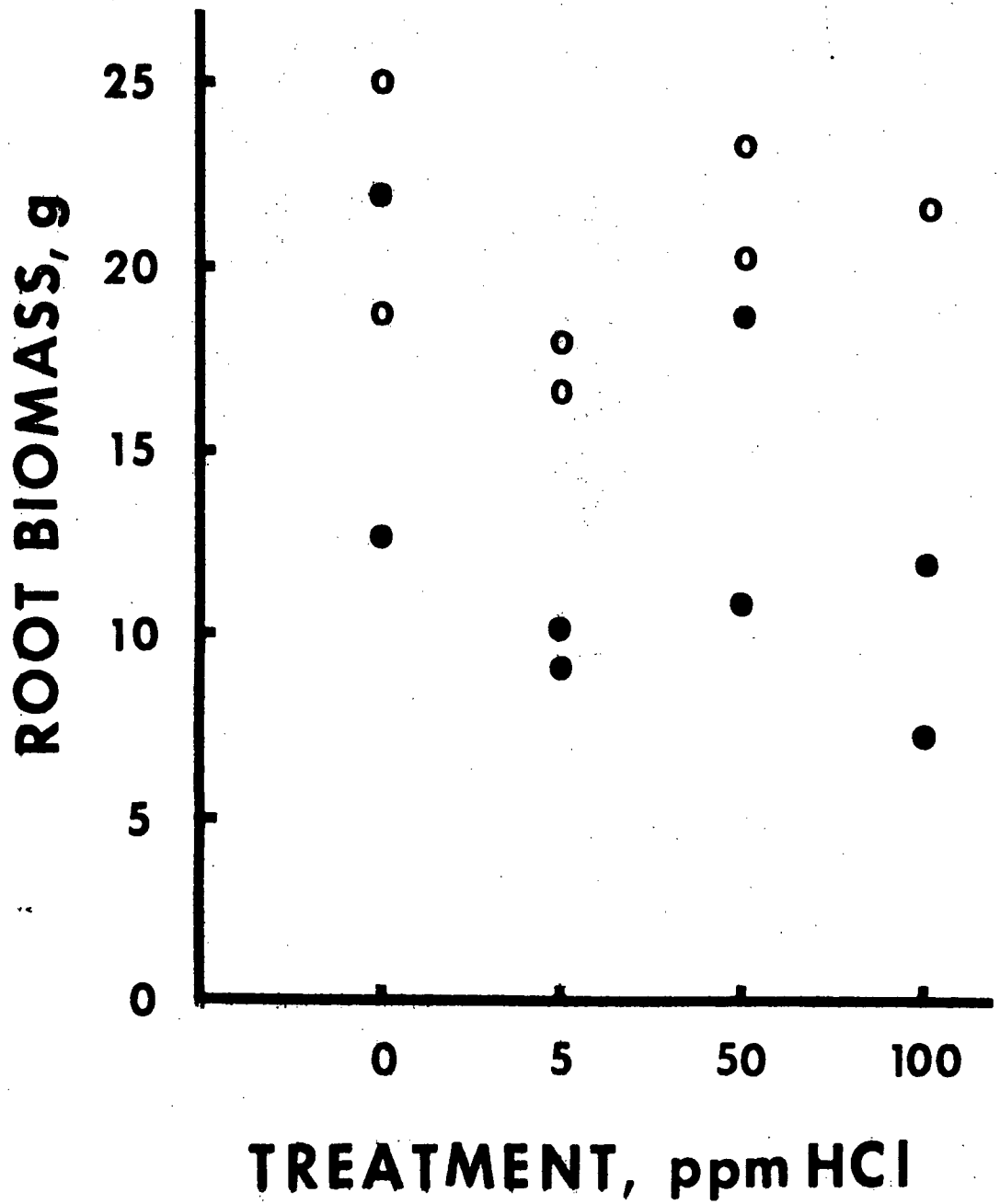
Table 6. Summary of analysis of litter on plots in pine flatwoods. Plots were exposed to SRM fuel exhaust in August 1974 and litter samples were collected in July 1975.

Treatment (ppm HCl)	Mean ±SE dry weight of litter components			
	Twigs	Leaves	Fine Material	Total
Control n = 4	14.62±4.41	34.00±9.08	13.07±1.18	61.77±13.68
5 ppm n = 4	22.87±10.06	40.05±8.66	22.50±3.95	85.42±17.59
50 ppm n = 4	13.07±4.76	34.40±8.34	21.10±3.95	68.57±15.45
100 ppm n = 2	9.00±0.30	24.40±1.60	19.40±2.20	52.80±0.30

Table 7. Summary of analysis of litter on plots in scrubby flatwoods. Plots were exposed to SRM fuel exhaust in August 1974 and litter samples were collected in July 1975.

Treatment	Mean ± SE dry weight of litter component			
	Twigs	Leaves	Fine Material	Total
Control n = 4	10.70±2.96	35.62±10.85	14.25±1.51	60.57±10.17
5 ppm n = 4	26.62±3.64	38.22±5.82	12.87±3.48	77.72±11.75
50 ppm n = 4	14.77±5.55	21.72±4.15	12.90±1.78	49.40±9.31
100 ppm n = 4	18.40±3.30	34.87±4.12	13.45±1.18	74.97±6.99

Fig. 1. Relationship between root biomass and treatment with SRM fuel emissions (ppm HCl). Replicate plots in the pine flatwoods are designated by open circles and plots in scrubby flatwoods by closed circles. Exposures were completed 1 year prior to determination of root biomass.


ROOT BIOMASS, g
25
20
15
10
5
0
0
5
50
100
TREATMENT, ppm HCl